HYDRAIN - INTEGRATED DRAINAGE DESIGN COMPUTER SYSTEM

VOLUME V. HY8 - CULVERTS

for:

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INTRODUCTION

HY8 is a collection of BASIC programs that allows the user to investigate the hydraulic performance of a culvert *system*. A culvert *system* is composed of the actual hydraulic structure, as well as hydrological inputs, storage and routing considerations, and energy dissipation devices and strategies. HY8 automates the methods presented in HDS-5, "Hydraulic Design of Highway Culverts," HEC-14, "Hydraulic Design of Energy Dissipators for Culverts and Channels," HEC-19, "Hydrology," and information published by pipe manufacturers pertaining to the culvert sizes and materials.[1,2,3,4] This volume of documentation describes the concepts and theories used within HY8. The user may refer to the listed references for detailed explanations.

The documentation is divided into three additional sections: System overview, technical information, and user documentation. System overview provides insight into the capabilities and hydrological aspects covered in the program. The technical information section provides the user with equations and methodologies used by HY8 when performing a culvert analysis. The last section discusses how to apply the program, particularly as it pertains to the HYDRAIN microcomputer package.

The HY8 program runs on IBM PC/XT and compatible microcomputers. It is designed to run on MS-DOS version 2.1 (and higher). HY8 Versions 3.1 and higher have been developed and provided to the Federal Highway Administration (FHWA) for distribution. HY8 Versions 1.1, 2.1, and 3.0 were produced by the Pennsylvania State University in cooperation with FHWA. The HY8 Versions 3.0 and earlier versions were sponsored by the Rural Technical Assistance Program (RTAP) of the National Highway Institute under Project 18B administered by the Pennsylvania Department of Transportation.

Users can apply HY8 both as an interactive program and as a batch program. The program operates both as a stand-alone product and through HYDRAIN.

SYSTEM OVERVIEW

The FHWA has developed analytical and empirical techniques to aid in the hydraulic analysis and design of culverts. The design engineer can utilize the FHWA publications to analyze culverts for a single design discharge and, with some additional effort, develop a culvert performance curve. In addition, these techniques allow the consideration of inflow and outflow hydrographs, storage and routing, and energy dissipation. However, evaluating the performance of different culvert *systems* for several flow scenarios requires considerable effort. To take advantage of the microcomputer's ability to quickly and accurately solve these culvert *system* techniques, the HY8 program was developed.

HY8 is composed of four different programs, or modules. These four modules are: a culvert analysis module, a hydrograph generation module, a routing module, and an energy dissipation module. These are linked together as depicted in figure 1. The capabilities of each of these modules are discussed below.

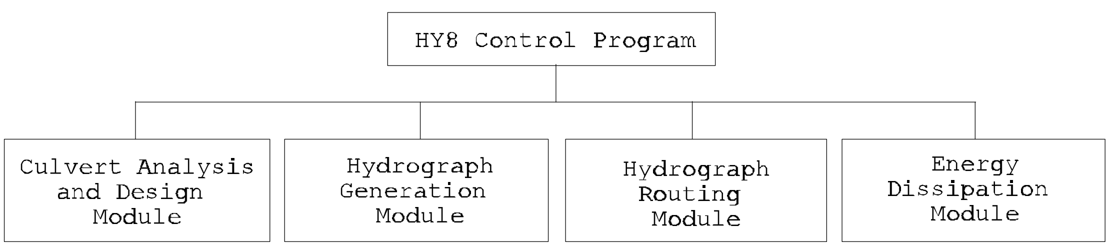

Figure 1. HY8 program modules.

CULVERT ANALYSIS AND DESIGN

The culvert analysis and design module allows the user to review the hydraulic characteristics of user-supplied culvert data. This module also permits minimization of culvert size based on an allowable headwater elevation. The program will compute culvert hydraulics for circular, rectangular, elliptical, arch, and user-defined geometry. Improved inlets can also be specified. The user will have the options of entering either a regular or an irregular cross section for calculating tailwater or a fixed tailwater may be specified.

A series of up to six parallel culvert systems, each having different inlets, inlet elevations, outlets, outlet elevations, lengths, and cross-sectional shape characteristics (e.g., diameter), can be analyzed. Each culvert system may consist of several barrels.

There are four main groups of data to be entered into the module: design flow data, initial culvert data, downstream channel data, and roadway data. These data are entered to the program through a series of data menus and data screens. The data can be edited from a summary screen. Output screens contain computed culvert hydraulics, while help files guide the user through the program. Each screen menu contains several options to match the desired culvert configuration while the data screens prompt the user for specific dimensions and coordinates.

From the data screens, the program calculates the inlet control and outlet control headwater elevations for a given flow. These elevations are compared and the larger of the two is used as the controlling headwater elevation. Tailwater effects are taken into consideration when calculating these elevations. The program develops culvert performance data with or without overtopping. If the controlling headwater elevation overtops the roadway embankment, an overtopping analysis is done in which flow is balanced between the culvert discharge and the discharge over the roadway.

In addition to developing performance curves, the program generates rating curves for uniform flow, velocity, and maximum shear for the downstream channel. Culvert outlet velocities, inlet control head, and outlet control head are also calculated. Several of these curves can be displayed on the screen for visual inspection of the results.

Finally, the culvert analysis module can assist in the design of a culvert through a "minimization" routine. The major constraints in this option are peak or design flow and allowable headwater. To design a culvert that passes the peak flow, the user enters an allowable headwater. The program will increase or decrease the culvert size so that a maximum headwater elevation that is less than the allowable headwater is calculated. The program recomputes associated hydraulic parameters for the design discharge when the minimization routine is activated.

HYDROGRAPH GENERATION AND ROUTING

The hydrologic module generates a storm hydrograph that can be used singly or as input into culvert routing analyses. The hydrograph is generated using methods found in the FHWA HEC-19 document.[3] Main input parameters in this module are watershed characteristics such as drainage area, slope, curve number, watershed distribution, coefficient of abstraction and base flow. From these parameters, a storm hyetograph and hydrograph are produced. An option allows a user-defined storm hyetograph to be entered from which a hydrograph is produced. As a final alternative, the user can enter a hydrograph.

The routing module uses the culvert data collected in the first module and the hydrograph generated in the second module to calculate storage and outflow hydrograph characteristics. The routing is performed using the storage indication (modified Puls) method. Four options are available to determine the upstream stage-storage relationships. These four options are: employing the prism method, entering a surface area-versus-elevation curve, entering a volume-versus-elevation curve, and providing stream cross-section data. The prism method uses the upstream channel slope and a rectangular or triangular shape to propagate a geometric shape (or prismatic section) upstream. In this manner, volumetric relationships can be calculated for a given elevation. The next two options employ user-supplied data to determine the volumetric relationship. The final option uses actual upstream cross section profiles to calculate the stage-storage relationship. Given some ingenuity, this option could be used to design a stormwater detention basin.

Note: Regardless of storage volume calculation method used, HY8 converts the data entered into storage volumes at even 1-ft (or 0.3048-m intervals if data are in SI units). If this procedure results in a storage depth shallower than 1-ft (0.3048 m), the user is notified and instructed to re-enter storage volume data with greater depth.

Users should also be aware how HY8 uses input hydrograph to be routed. The initial input hydrograph flow value is assumed to be the base flow. If the storage reservoir has not been depleted by the final time step in the input hydrograph, HY8 assumes an input flow equal to the initial value of the input hydrograph (base flow) for as many time steps as are required to deplete the storage reservoir.

ENERGY DISSIPATION

The final module permits the design and analysis of an energy dissipator at the culvert outlet. It follows the design procedures used in FHWA publication HEC-14.[2] Similar to the routing module, this module needs the performance curve generated from a culvert analysis file to perform the energy dissipator design and analysis. If there is more than one culvert *system* in the culvert analysis file, the user has to specify which system is used for the design. The program will design a dissipator for only one culvert at a time. The user can select several options from within this module. These options are: designing an external dissipator, designing an internal dissipator, estimating the scour hole geometry, and modifying hydraulic aspects of the culvert being analyzed.

TECHNICAL INFORMATION

This section describes the technical methods used by HY8 to analyze culvert *systems*. Analysis of culverts using a peak flow is discussed along with hydrograph generation and routing and energy dissipator design. Culvert analysis involves calculating the inlet and outlet control headwater elevations for the given flow. These elevations are compared, and the larger of the two is used as the controlling headwater elevation. Tailwater effects are taken into consideration when calculating these elevations. If the controlling headwater elevation overtops the roadway embankment, an overtopping analysis is done in which flow is balanced between the culvert discharge and the surcharge over the roadway. A balancing technique is used in the case of multiple systems.

HY8 performs calculations using equations derived in English units. HY8 allows the user to input SI data and gives reports using SI data, if the user desires. The Benchmark Examples in appendix A of this volume illustrate the use of HY8 in SI units.

INLET CONTROL

Using regression analysis, FHWA produced fifth-degree polynomial equations to model the inlet control headwater for a given flow. The regression equations have been developed for the range of inlet heads from one half to three times the culvert rise. Analytical equations, based on minimum energy principles, are matched to the regression equations to model flows that create inlet control heads outside of the regression data range.

For culvert discharges within the range of the regression analysis, the FHWA equation gives a direct solution for inlet head. The regression equations are applied at headwaters between 0.5 and 3.0 culvert depths, and are of the form:

$$H_{wi} = \left[a + (bzF) + c(zF)^2 + d(zF)^3 + e(zF)^4 + f(zF)^5 - 0.5S \right] \times D \qquad (1)$$

Where:

H_{wi}	=	The inlet control headwater, m.
D	=	The rise of the culvert barrel, m.
a to f	=	Regression coefficients for each type of culvert.
F	=	$Q/D^{5/2}$ for circular culverts, or $Q/(BD^{3/2})$ for box arch pipe culverts, Where: Q = flow, m^3/s. D = culvert rise, m. B = culvert span, m.
S	=	Barrel slope, m/m.
z	=	1.81130889 (metric conversion constant).

The regression coefficients are tabulated in table 1 along with the corresponding chart and scale numbers from HDS-5. These coefficients have been compiled, and in some cases corrected, from a variety of sources for use in HY8.[7, 8, 9, 10, 11]

For discharges that create inlet control heads above the regression equation limits, headwater to culvert rise ratios greater than 3.0, an orifice equation is used to estimate headwater. The potential head for the orifice equation is given by the difference of the water surface elevation and the elevation of the center of the circular pipe. For noncircular culverts the potential head is determined to be from the center of the culvert, which is approximated by the sum of the invert elevation and one half the rise of the culvert. The orifice equation used in the program is of the form:

$$H_{wi} = \left[\frac{Q}{k}\right]^2 + 0.5 \ x \ D \qquad (2)$$

Where:

H_{wi}	=	Inlet control headwater, m.
Q	=	Design discharge, m^3/s.
k	=	Coefficient based on the discharge and culvert rise.
D	=	Rise of culvert, m.

The coefficient, **k**, is determined by setting the orifice equation equal to the regression equation at the upper limit of the regression equation. The coefficient is calculated as:

$$k = \frac{Q_{3.0}}{\sqrt{2.5 \ x \ D}} \qquad (3)$$

Where:

$Q_{3.0}$	=	Discharge from regression equation (1) at H_{wi} / D = 3.0, m^3/s.

For discharges corresponding to inlet control heads less than half the rise of the culvert, an open channel flow minimum energy equation is used with the addition of a velocity head loss coefficient. Critical depth for the minimum energy equation is determined from the following condition:

$$F_r^2 = \frac{Q^2 \times T}{g \times A^3} = 1 \qquad (4)$$

Table 1. Polynomial coefficients.

HDS-5 Chart No.	HDS-5 Scale	a	b	c	d	e	f
1	1	0.087483	0.706578	-0.2533	0.0667	-0.00662	0.000251
	2	0.114099	0.653562	-0.2336	0.059772	-0.00616	0.000243
	3	0.108786	0.662381	-0.2338	0.057959	-0.00558	0.000205
2	1	0.167433	0.538595	-0.14937	0.039154	-0.00344	0.000116
	2	0.107137	0.757789	-0.3615	0.123393	-0.01606	0.000767
	3	0.187321	0.567719	-0.15654	0.044505	-0.00344	0.00009
3	A	0.063343	0.766512	-0.316097	0.08767	-0.00984	0.000417
	B	0.081730	0.698353	-0.25368	0.065125	-0.0072	0.000312
8	1	0.072493	0.507087	-0.11747	0.02217	-0.00149	0.000038
	2	0.122117	0.505435	-0.10856	0.020781	-0.00137	0.0000346
	3	0.144138	0.461363	-0.09215	0.020003	-0.00136	0.000036
9	1	0.156609	0.398935	-0.06404	0.011201	-0.00064	0.000015
10	2	0.156609	0.398935	-0.06404	0.011201	-0.00064	0.000015
11	2	0.122117	0.505435	-0.10856	0.020781	-0.00137	0.000034
	4	0.089563	0.441247	-0.07435	0.012732	-0.00076	0.000018
12	2	0.156698	0.398935	-0.06404	0.011201	-0.00064	0.000015
29	1	0.13432	0.55951	-0.1578	0.03967	-0.0034	0.00011
	2	0.15067	0.50311	-0.12068	0.02566	-0.00189	0.00005
	3	0.03817	0.84684	-0.32139	0.0755	-0.00729	0.00027
30	1	0.13432	0.55951	-0.1578	0.03967	-0.0034	0.00011
	2	0.15067	0.50311	-0.12068	0.02566	-0.00189	0.00005
	3	0.03817	0.84684	-0.32139	0.0755	-0.00729	0.00027
34	1	0.111281	0.610579	-0.194937	0.051289	-0.00481	0.000169
	2	0.083301	0.795145	-0.43408	0.163774	-0.02491	0.001411
	3	0.089053	0.712545	-0.27092	0.792502	-0.00798	0.000293
35	1	0.089053	0.712545	-0.27092	0.792502	-0.00798	0.000293
36	1	0.089053	0.712545	-0.27092	0.792502	-0.00798	0.000293
41,42, 43	1	0.111281	0.610579	-0.104937	0.051289	-0.00481	0.000169
	2	0.083301	0.795145	-0.43408	0.163774	-0.02491	0.001411
	3	0.089053	0.712545	-0.27092	0.792502	-0.00798	0.000293
55	1	0.2115	0.3927	-0.0414	0.0042	0.0003	-0.00003
	2	0.2252	0.3471	-0.0252	0.0011	0.0005	-0.00003

Note: ***Values for English system of units. Equation (1) is valid with these coefficients when the metric conversion constant (z) is used.***

Where:

F_r = The Froude number (equal to one in this case).
Q = The culvert flow rate, m^3/s.
A = The culvert's cross sectional flow area, m^2.
T = The culvert's cross section top width, m.
g = The gravitational acceleration (9.81 m/s^2).

Based on the critical values of depth and velocity described in equation (4), the following minimum energy equation is used to estimate headwater:

$$H_{wi} = d_c + (1 + K_e) \frac{V_c^2}{2 \times g} \qquad (5)$$

Where:

d_c = The critical depth at culvert entrance for given discharge, m.
K_e = The entrance loss coefficient.
V_c = The velocity at critical depth, m/s.

The entrance loss coefficient is determined by setting the minimum energy equation equal to the regression equation at one half the rise, which is the lower limit of the regression equation. The coefficient is calculated using the following equation:

$$K_e = \left[\frac{(0.5 \times D - d_c) \times 2 \times g}{\left[\frac{Q_{0.5}^2}{A_c^2} \right]} - 1 \right] \qquad (6)$$

Where:

$Q_{0.5}$ = Discharge computed using regression equation at a H_{wi} /D value of 0.5 m^3/s.
A_c = Cross-section area at critical flow, m^2.

The minimum energy equation, with the velocity head loss adjusted by K_e, generally describes the low flow portion of the inlet control headwater curve; however, numerical errors in the calculation of flow for very small depths tends to increase the velocity head as the flow approaches zero. This presents little or no problem in most single system cases since the flows that cause this are relatively small. In many of the calculations required for the solution of multiple culverts, the inlet control curve must decrease continuously to zero for the iterative calculations to converge. Therefore, modifications to this equation have been made to force the velocity head to continually decrease to zero as the flow approaches zero.

As the flow depth becomes very shallow in the culvert, the rate of width to depth of flow ratio increases greatly. As the flow approaches zero the culvert can be assumed to be very wide and the wide channel approximation of minimum energy is used.

$$E = 1.5 \times d_c \tag{7}$$

Where:

E = The approximation of the minimum energy, m.
d_c = The critical depth, m.

The critical depth is continuously decreasing and approaches zero as the flow approaches zero. The headwater calculation between flow at zero and half the rise must be a combination of the minimum energy calculation with the velocity head loss equation and the wide channel approximation minimum energy equation. This can be accomplished by a linear weighting of the equations in the low flow range.

In the range of flows between 15 percent of the flow that causes an inlet head elevation of one half the culvert rise to zero flow, the velocity head is gradually converted to one half the critical depth. First, the fractional contribution of a given flow, Q, in relation with the 15-percent flow is calculated;

$$Q_{frac} = \frac{0.15 \times Q_{0.5} - Q}{0.15 \times Q_{0.5}} \tag{8}$$

Where:

Q_{frac} = The fractional contribution of a given flow.
$Q_{0.5}$ = The discharge that creates inlet control head of one half the rise of the culvert, m^3/s.
Q = A given discharge, between 0 and 15 percent of $Q_{0.5}$, m^3/s.

Next, a velocity head coefficient, based on the fractional contribution and the velocity head is computed;

$$C_{vh} = \frac{1 - Q_{frac}}{1 + \left[\frac{V^2}{2 \times g} \ x \ Q_{frac} \right]} \tag{9}$$

Where:

C_{vh}	=	The velocity head coefficient.
Q_{frac}	=	The fractional contribution of a given flow.
V	=	The average velocity, m/s.

Finally, the corrected velocity head can be calculated;

$$\frac{V_{corr}^2}{2 \times g} = \left[Q_{frac} \times 0.5 \times d_c\right] + \left[\frac{V^2}{2 \times g} \times C_{vh}\right] \qquad (10)$$

Where:

V_{corr}	=	The corrected velocity, m.
Q_{frac}	=	The fractional contribution of a given flow.
d_c	=	The critical depth for given flow, m.

As the discharge, Q, approaches zero, Q_{frac} approaches unity and C_{vh} vanishes. Inversely, as Q approaches $Q_{0.5}$, Q_{frac} vanishes and C_{vh} approaches unity. From equation (10), it can be said that for low flows (i.e., less than 15 percent of $Q_{0.5}$), the inlet control equation becomes:

$$H_{wi} = d_c + (1 + C_{vh}) \times \frac{V_{corr}^2}{2 \times g} \qquad (11)$$

Where:

H_{wi}	=	The inlet control headwater, m.
d_c	=	The critical depth, m.
C_{vh}	=	The velocity head coefficient.
V_{corr}	=	The corrected velocity, m/s.

DETERMINING INLET OR OUTLET CONTROL

On mild slopes, the direct step method is used to calculate water-surface profiles when open channel flow occurs in the culverts. That is, when a portion or all of the culvert is flowing less than full, water-surface profile computations are used to compute friction losses. The water-surface profile computations begin at the culvert barrel exit and proceed upstream for culverts under outlet control. For inlet control, computations commence at the inlet and proceed downstream. If the water surface intersects the crown of the culvert, pressure flow is calculated for the remaining length of the culvert.

If the slope of the culvert is steep, then a check is made to determine if the inlet is submerged by the tailwater. In most cases where the slope is supercritical the culvert is in inlet control. The program will proceed with head loss calculations from the outlet toward the inlet until either the entrance is reached or critical depth is reached suggesting that a hydraulic jump has formed in the culvert if the outlet is submerged. If the entrance is reached before critical depth, then the inlet control point has been submerged by the tailwater and friction effects force outlet control. When critical depth is calculated in the culvert, the flow is controlled at the inlet. The outlet control elevation output by the computer is the sum of minimum energy and an inlet loss at the location where the critical depth has been calculated.

OUTLET CONTROL

Headwater elevation under outlet control is determined by adding the friction losses in the pipe barrel, the entrance loss, and exit loss to the tailwater elevation. For the losses to affect the headwater, the flow through the culvert must be subcritical. The program initially determines whether the culvert slope is hydraulically mild or steep and whether the culvert outlet crown is submerged or unsubmerged (i.e., whether the downstream water surface is above or below the outlet crown).

The procedure for determining outlet depth is based on the submerged or unsubmerged condition of the culvert outlet and is summarized in figure 2. Critical depth and normal depth are computed and compared to determine if the culvert assumes a mild or steep slope. Next, the program determines whether the inlet and outlet are submerged or unsubmerged. Outlet depth is determined based on the combination of possible tailwater conditions.

If the culvert exit is submerged, then at least part of the barrel is flowing full and pressure flow computations are performed to determine the length of the full flow section. When only a portion of the culvert is flowing full, water-surface profile calculations are used to compute the friction losses in the open channel flow section. If the length of the full flow section is equal to the full length of the culvert, then pressure flow exists throughout the culvert.

In steep culverts, a hydraulic jump may form if the flow depth is less than critical. If the jump is detected in the culvert then the culvert is controlled at the inlet. However, under this circumstance, the energy elevation at the jump is output for the outlet control elevation. If the tailwater is high enough, the jump may submerge the inlet causing the headwater elevation to be controlled by the outlet.

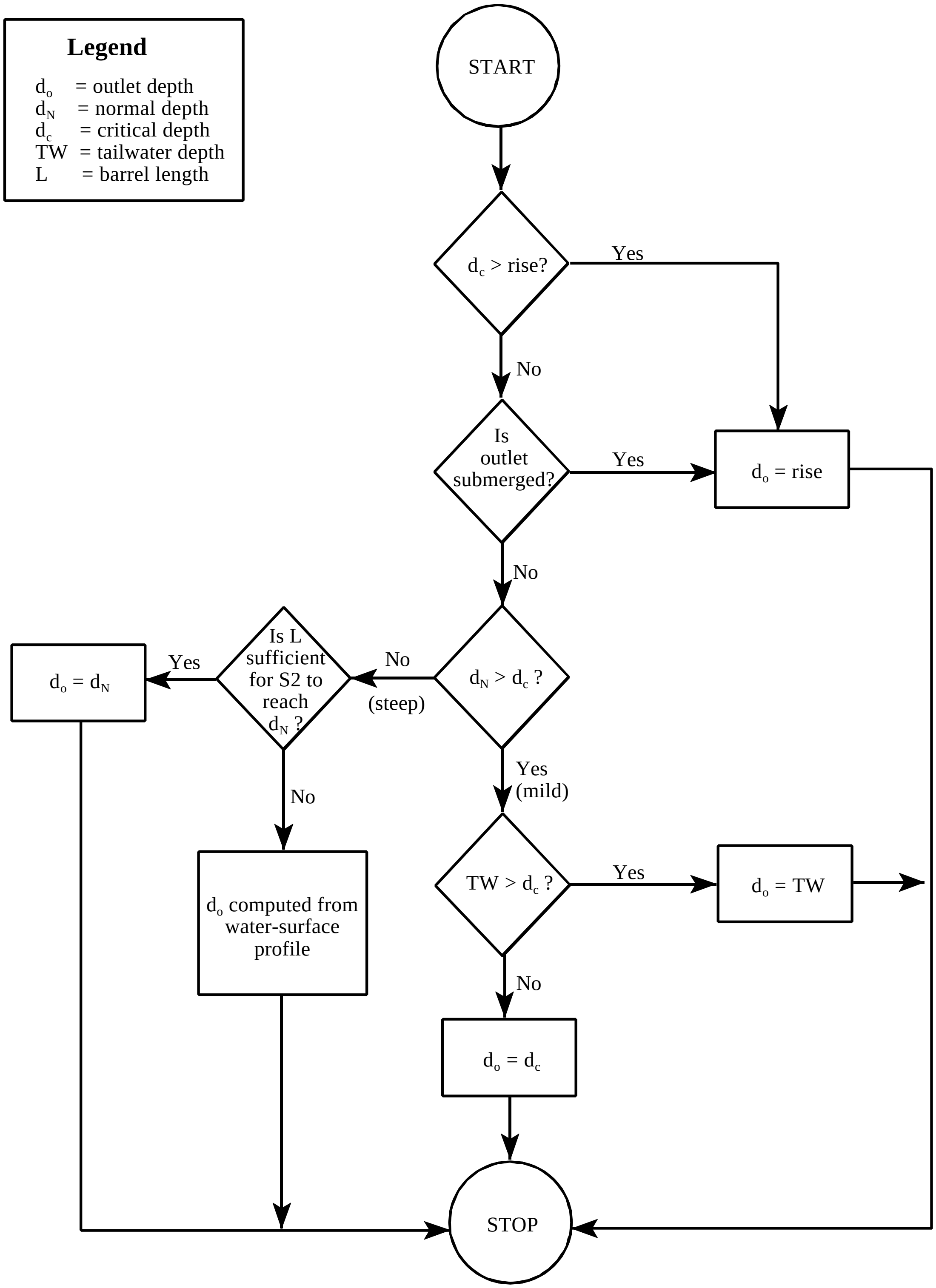

Figure 2. Determination of outlet depth.

Friction losses in the barrel are determined by manipulating Manning's formula to solve for friction slope:

$$S_f = \left[\frac{Q \times n}{A \times R_h^{0.67}} \right]^2 \tag{12}$$

Where:

S_f	=	The friction slope, m/m.
Q	=	The culvert barrel discharge, m^3/s.
n	=	Manning's roughness coefficient.
A	=	The cross section flow area, m^2.
R_h	=	The hydraulic radius of the culvert, m.

If the barrel is flowing full, the friction slope is constant over the length of the full-flowing barrel and frictional head loss can be computed by the following:

$$H_f = S_f \times L \tag{13}$$

Where:

H_f	=	The head loss due to friction in the culvert barrel, m.
S_f	=	The friction slope, m/m.
L	=	The length, m, of culvert containing full flow.

If open channel flow is occurring in the culvert, the hydraulic parameters are changing with flow depth along the length of the culvert. The friction losses are determined by summing the incremental changes in head loss using the direct step method. The incremental head loss is calculated by:

$$\delta H_f = S_f \times \delta L \tag{14}$$

Where:

δH_f	=	The incremental head loss, m.
S_f	=	The friction slope, m/m, at δL.
δL	=	The incremental change in length, m.

The open channel barrel loss calculations for outlet control proceed as follows:

1. An increment of head loss is determined.

2. The friction slope is calculated at the outlet.

3. The incremental length of culvert is calculated from the friction slope and the specified head loss.

4. A new friction slope is calculated at the distance computed in step three.

5. From the specified head loss and the friction slope determined in step four, an incremental length is calculated and added to the length calculated previously.

6. The incremental head losses are summed and steps four and five are repeated until the summed length from the outlet is greater than the length of the culvert or until the head losses in the culvert cause the water surface to intersect the crown of the culvert (beginning of pressure flow).

The sum of the incremental head losses computed is the frictional head loss through the open channel flow section of the culvert barrel. If a portion of the barrel is flowing full then the full flow head loss is computed and added to the open channel head loss for the total barrel friction loss.

Losses at the culvert entrance and exit are computed by the product of a loss coefficient and the velocity at the entrance and exit. The entrance loss equation used in the program is:

$$H_e = K_e \times \frac{V^2}{2 \times g} \tag{15}$$

Where:

H_e	=	The entrance head loss, m.
K_e	=	The entrance loss coefficient.
V	=	The flow velocity just inside culvert barrel, m/s.
g	=	The gravitational acceleration (9.81 m/s^2).

Values of K_e are selected by HY8 from the values in HDS-5 based on culvert shape and entrance condition.

Similarly, the exit loss equation is:

$$H_o = 1.0 \times \frac{V^2}{2 \times g} \tag{16}$$

Where:

H_o	=	The exit head loss, m.
V	=	The flow velocity inside the culvert barrel upstream of the outlet, m/s.

Outlet control water surface elevation is computed as the sum of all losses and the outlet depth:

$$H_{wo} = H_f + H_e + H_o + h_o \tag{17}$$

Where:

h_o	=	Tailwater depth or (d_c + rise)/2, m.

DOWNSTREAM CHANNEL

The water-surface elevation in the downstream channel may influence the culvert discharge, therefore, it is important to have a reasonable estimate of the water-surface elevation and the velocity in the downstream channel. The downstream water-surface elevation is important in determining the effects of tailwater on culvert performance. Velocity, shear stress, and Froude number in the channel are important in determining channel stability. The program will calculate uniform flow (normal depth) elevation, velocity, shear, and Froude number values; however, calculations for the culvert performance curve use only the elevation of the water surface.

The uniform flow calculations are performed using Manning's equation. Area and hydraulic radius are functions of water-surface elevation and channel geometry. Since the determination of water-surface elevation given flow is a direct solution in Manning's formula for only the simplest cases, an iterative technique is used to determine water-surface elevation. For channels of simple cross-sectional geometry (trapezoidal, rectangular, and triangular) the area and hydraulic radius calculations are calculated by a single routine. The determination of the water-surface elevation for an irregular shaped channel is more involved.

Under many flow conditions in natural channels, the flow is conveyed in subchannels and overbank regions that have significantly different hydraulic capacities than the main channel. The irregular channel algorithm can calculate uniform flow water-surface elevations with three separate subchannels using geometric principles to balance the conveyances in the subchannels. Velocity calculations for the simple cross-sectional geometries are average velocities. Velocity calculations for the irregular-shaped channels are average velocities for the main channel.

Shear is calculated by the following equation:

$$\tau = \gamma \times S_f \times TW \tag{18}$$

Where:

τ	=	The maximum shear, in Pa (N/m^2).
γ	=	The specific weight of water, (9800 N/m^3).
S_f	=	The friction slope (equal to channel slope for uniform flow), m/m.
TW	=	The tailwater depth, or the maximum depth of flow occurring in the natural channel just beyond the culvert outlet, m.

Froude number is determined from the following equation:

$$F_r^2 = \left[\frac{Q^2 \times T}{g \times A^3}\right] \tag{19}$$

Where:

F_r	=	The Froude number.
Q	=	The discharge in the channel, m^3/s.
T	=	The channel cross section's top width, m.
A	=	The channel's waterway cross sectional area, m^2.

ROADWAY OVERTOPPING

The flow that overtops an embankment is analogous to that of a broad crested weir. The following weir equation is used to determine flow over embankments:

$$Q_o = \frac{C_d \times L \times H_{wr}^{\frac{3}{2}}}{z} \tag{20}$$

Where:

Q_o	=	The discharge over embankment, m^3/s.
C_d	=	The discharge coefficient (weir coefficient).
L	=	The length of weir crest, m.
H_{wr}	=	The upstream head above embankment crest, m.
z	=	0.81130889 (metric conversion constant).

The program has two options for selection of the discharge coefficient. The user can specify the surface type and allow the program to determine the coefficient from internal tables or the user can input a discharge coefficient. Coefficients determined by the program are interpolated from data points taken from the FHWA discharge coefficient curves for paved and gravel roadway surfaces.[1] The tables are based on the headwater elevation and the roadway width. The coefficients are modified for tailwater submergence by multiplying the coefficients by a submergence factor which is interpolated from data taken from the submergence factor curves for paved and gravel roadways. The coefficients entered by the user are also multiplied by a submergence factor that is interpolated from the data for the gravel roadway surfaces.

For convenience in computations an assumption of a constant roadway surface elevation for the crest of the weir is common, although the section of the roadway that becomes overtopped is usually the low portion of a vertical curve. With little additional computational effort, the calculation of flow can be integrated over the roadway profile described by several coordinates that more accurately define the roadway surface. If given a set of roadway profile coordinates and other data to describe headwater elevation and the coefficient of discharge, the program will integrate the weir equation to determine flow between each of the coordinates and sum the flows to give a total flow over the entire roadway profile.

A four point Gaussian quadrature routine is used to integrate between any two coordinate points. If the information for the roadway surface and tailwater is given, the weir coefficient and submergence reduction is computed at each integration point.

MULTIPLE BARREL ANALYSIS

In some cases, an analysis of flow through two or more barrels and/or over the roadway may be necessary. If tailwater effects are negligible, the determination of headwater elevation and flow conveyed through each of the conduits and over the roadway may be computed by adding performance curves. If each of the barrels is considered identical, the symmetry of the system can be used by dividing the flow by the number of barrels and proceeding with calculations as for a single barrel. However, if there is an effect on the conveyance by the tailwater and the culverts are different, then the simple addition of performance curves may be considerably erroneous. For a given flow, the tailwater elevation can be approximated from normal depth or backwater calculations. Flows in each of the culverts must be such that the total head loss in each culvert is identical (the difference between headwater and tailwater elevations) and the total flow conveyed must be equal to the sum of the flows through each of the culverts and over the roadway.

The tailwater and headwater potential are identical for each of the culverts. Given the assumption of no interference of one culvert with another at the inlet or outlet, the head loss experienced in each of the culverts must be the same. The total flow must be the sum of the flows through each culvert. Streeter and Wylie give an iterative procedure for solving the head loss and flow in similar parallel pipe systems.[5] With slight modification to the parallel pipe procedure, the following is the basis for the multiple barrel iterative solution technique:

1. Assume a flow through the control barrel, which is the barrel with the lowest invert.

2. Determine the head loss through the control barrel and the headwater elevation caused by that head loss.

3. Determine flow in the other barrel(s) based on the headwater elevation calculated from the control barrel.

4. Distribute flows by the following equation:

$$Q_i = \frac{Q_{ic}}{\Sigma Q_{ic}} \tag{21}$$

Where:

Q_i	=	The adjusted flow through barrel i, m^3/s.
Q_{ic}	=	The calculated flow through barrel i, m^3/s.
ΣQ_{ic}	=	The sum of the calculated flows, m^3/s.

5. Use the adjusted flow through the control barrel as the assumed flow in the control barrel and repeat the procedure until the difference in sum of the calculated flows and the given flow and the difference in the headwater elevations from successive iterations are within acceptable limits.

This technique converges rapidly and is stable if the rate of head loss change to discharge change is smaller for the controlling barrel than for the other barrels. In most cases, this translates to the controlling barrel diameter being larger than the diameter of the other barrels. When the controlling barrel diameter becomes much less than that of another barrel, the solution may oscillate. In most practical applications the barrel with the lowest invert is the largest or approximately the same size as the other barrels. However, it is desired that the same iterative procedure be used to balance flows if the roadway is overtopped.

Initial convergence limits, set on both headwater elevation and percent of total discharge, are well within the accuracy of the Manning's friction coefficient, n. A limit of 50 iterations is set after which the process is aborted and the program proceeds with other calculations. A summary of iterative solution errors will show the error limits for the solution. The greater the number of barrels in the solution, the less stringent the convergence criteria must. The criterion for terminating the successive headwater calculations is the iteration where the difference of the prior headwater and the newly computed headwater is less than the empirical value of 0.01 times the number of barrels. Similarly, the criteria for convergence on percent total flow is when the ratio of total calculated flow to total flow is less than one percent times the number of barrels.

After the tabulation of the performance curve for multiple culverts, a table of errors for the iterative technique is given. This table includes error of percent total flow and headwater elevation error.

MINIMIZATION OF CULVERT SIZE

A culvert minimization routine permits a steady-state culvert design calculation to be made. The minimization routine uses an allowable headwater elevation and design discharge as the controlling hydraulic factors to adjust the culvert size. The culvert size that minimizes the difference between the maximum headwater calculation and the user-supplied allowable headwater is the result. Hydraulic parameters are recomputed when the minimization routine is activated. These parameters include: allowable headwater elevation, controlling headwater elevation (which will be lower than the allowable headwater elevation), inlet and outlet control elevations, culvert flow velocity, channel flow velocity, design discharge, channel slope, culvert flow depth, channel flow depth, normal flow depth, and critical flow depth.

HYDROGRAPH GENERATION AND ROUTING

The hydrograph generation and routing modules permit a dynamic evaluation of culvert system performance. Hydrographs may be developed within HY8 based on drainage area characteristics and rainfall patterns or they may be incorporated from other sources such as the HYDRO program (also part of HYDRAIN). For technical documentation of the internal generation of hydrographs, the user is referred to Masch.[3]

Hydrograph routing is accomplished using hydrographs developed in the hydrograph generation module and the site and culvert characteristics of interest. The hydrograph is routed through the system using the storage indication method. Results include variations in headwater and outflow as a function of time. **(Caution: In HY8, hand-inputted hydrographs force this computational time increment. Make sure there are sufficient points or routing will be inaccurate.)**

ENERGY DISSIPATOR DESIGN

HY8 follows the design procedures presented in HEC-14.[2] Restrictions and limitations on these dissipators are presented in a table format for each dissipator category within the HY8 software. Hydraulic parameters computed in the culvert design program are imported into this module. The following categories of energy dissipators are available:

(1) Internal Energy Dissipators (Box or Circular shapes):
- Increased Resistance
- Tumbling Flow

(2) External Energy Dissipators:

(A) Drop Structures
- Box Drop-Structure
- Straight Drop-Structure

(B) Stilling Basin:
- USBR Type 2 Basin
- USBR Type 3 Basin
- USBR Type 4 Basin
- S.A.F. Basin

(C) At-Streambed-Level Structures
- CSU Basin
- Riprap Basin
- Contra Costa
- USBR Type 6

Hydrologic data and soil type characteristics are used to estimate the scour hole geometry at the culvert outlet. HY8 allows the user to change the culvert discharge, culvert outlet velocity and depth of water at culvert outlet. As mentioned before, the user can switch between the differing culvert systems if more than one was entered in the culvert analysis module.

USER DOCUMENTATION

For those users who have obtained HY8 as part of the FHWA's **HYDRAIN** package, the following section discusses the procedures for accessing HY8 through the HYDRAIN System Shell. The user is referred to the HYDRAIN documentation if additional information is required on the working of the HYDRAIN System Shell.

The interactive capabilities of HY8 provide much of ease (self contained within the menu screens and helps) in performing an analysis . This interactive capability lessens the need for a users manual. Data entry is accomplished through the use of menus and prompts generated by the program. The program has some error and range checking capabilities for ensuring that only realistic values are entered by the user. Data can be edited and summary tables of input data and output results are generated periodically throughout the data entry process. HY8 also can be operated in a batch mode. In this mode, the user creates an input file and uses HY8 to process the data into an output screen or file.

THE HYDRAIN ENVIRONMENT

HY8, as well as the other HYDRAIN software packages, are activated through the use of what is known as the HYDRAIN "shell." This shell is a separate program that ties the system components together and allows them to be accessed. Before work on a specific HY8 example can begin, the HYDRAIN shell must first be entered. This process is begun, from DOS by entering the C:\HYDRAIN directory, typing the command **HYDRAIN**. A screen will appear showing the member sponsors of the Pooled Fund Project. Another <Enter> reveals a message (a "disclaimer"). A third <Enter> will place the user in the <u>Main Menu</u>.

After the introductory screens have been cleared the user enters the <u>Main Menu</u> which contains the following choices:

- File - File operations, DOS shell, Exit.
- Editor - input or edit data for HYDRA, WSPRO, **HY8**, HYDRO, or HYCHL batch programs.
- Analyze - run HYDRA, WSPRO, **HY8**, HYDRO, HYCHL, NFF, or HYEQT.

- Utilities - System maintenance, HYDRAIN setup.

- Help - long help files for selected topics in HYDRAIN.

Selection of an option within the Main Menu is accomplished by using the ARROW keys to move the cursor to the desired procedure or by striking the highlighted letter of the desired option. As each of the procedural options is highlighted by the cursor, a menu of the options within the specific procedural category are displayed.

As mentioned earlier, although HY8 has an interactive program, it can also be run in batch mode. To access the HY8 interactive mode, move the cursor to the Analyze option and strike <Enter>. Once within the Analyze pulldown menu, move to the HY8 option with the "down" ARROW cursor key. Once the menu bar is over the **HY8** field, striking <Enter> will initiate the HY8 program.

At times, there may be insufficient RAM to run HY8 within the HYDRAIN shell. If this problem is encountered, HY8 can be executed without the shell.

EXECUTING HY8 WITHOUT THE HYDRAIN SYSTEM SHELL

HY8 can be executed apart from the HYDRAIN System Shell by moving to the default HY8 directory, typing the command **HY8** and striking <Enter>. A good idea is to place the HY8 directory name into the PATH statement, usually found in the AUTOEXEC.BAT file.

HY8 PROGRAM MENU

The program begins in the HY8 option menu. It is at this juncture that the user has access to the modules discussed earlier. Since the vast majority of the analyses are performed in the culvert analysis module, it will be discussed in more detail than the other modules.

Culvert Analysis (and Design) Module

The culvert analysis section of the program allows for data entry, editing, and analysis. The user is sequentially led through the analysis process and is provided with an understanding of the necessary procedures used in the analysis of a culvert.

The option menu consists of six sections; Culvert File, Available Files, Design Options, Single Culvert, Multiple Culverts, and Default Options. The user may end HY8 by pressing <Q> or may view documentation by pressing <ENTER>.

The Culvert File section contains choices which enable users to <C>reate a new input file, <E>dit the available input file, load an input file by <N>ame, or choose an input file from a <D>irectory list.

The Available Files section indicates the names of the currently loaded Input (INP), output (PC), and Report (PRN or LST) files. If no input file is specified, one must either be loaded using the <N>ame or <D>irectory options or created using the <C>reate option. Once loaded, the available input file may be edited using the <E>dit option.

The Design Options section gives user access to the other three modules of HY8. <H>ydrograph allows generation of hydrograph files for use with HY8 and other programs. <R>outing allows the user to generate a routed hydrograph specifying upstream storage characteristics. <J> allows the user to design energy dissipators for culvert outfalls.

When creating a new culvert file (<C>reate under the Culvert File section), the user is asked to enter a performance curve discharge range which consists of minimum, maximum, and design flows. The maximum discharge allows the user to enter a discharge consistent with the maximum probable storm event.

Next, data concerning the culvert site are entered. There are two possible options for entering these data, the culvert-invert option and the embankment-toe option. With the culvert-invert option, the stations and elevations of the inlet and outlet are entered. The other option is to enter embankment and toe data which are used by the program to generate invert data for the inlet and outlet. One barrel is the default. This number can be edited to fit the user's desired number of barrels.

```
  CULVERT FILE: NHIRR       FHWA CULVERT ANALYSIS          DATE: 10-15-97
TAILWATER FILE: REGULAR       HY8, VERSION 6.1             CULVERT NO. 1 OF 1



                     CULVERT INVERT DATA


               NO.     ITEM                        VALUE

               <1> INLET STATION (m)                0.00
               <2> INLET ELEVATION (m)             30.00
               <3> OUTLET STATION (m)              60.00
               <4> OUTLET ELEVATION (m)            29.50
               <5> ENTER NUMBER OF BARRELS          1


                   <NUMBER> TO EDIT ITEM
                   <ENTER>  TO CONTINUE DATA INPUT
                   <ESC>    FOR SITE DATA OPTION MENU
```

Figure 3. Culvert invert data screen.

Following this series of screens, the culvert shape and dimensions are chosen along with the inlet type and culvert material. The program has a wide variety of shapes that can be used including; circular, box, elliptical, pipe arch, and irregular. Inlets can be conventional or improved with side tapering or slope tapering. Included in the inlet data is information on headwall and wingwall geometry. The culvert material data are used to determine a Manning's 'n' value. The culvert material option yields an 'n' value consistent with the culvert material chosen.

Downstream channel information is the next group of data to be entered. This information is used to generate a tailwater rating curve. First, a channel shape is chosen from one of the following possibilities; rectangular, trapezoidal, triangular, or irregular. The irregular channel can be described using x, y coordinates. There are also options to enter the user's own rating curve or a constant tailwater elevation. Two other pieces of information that are needed are the slope and Manning's 'n' value for the channel. From this data, a tailwater rating curve is developed in tabular form and can be plotted if graphics capabilities are available.

After returning to the culvert portion of the program with the rating curve, the user will be prompted for roadway data to be used in the overtopping analysis. A constant roadway elevation can be entered, or an irregular profile can be described. A weir coefficient and the embankment width are also needed for the overtopping analysis. The analysis is similar to that of a broad crested weir and similar data are needed. For weir coefficients, the user has the option to use the two preset coefficients for either paved or gravel roadway surfaces, or enter a user-defined value between 2.5 and 3.095.

From these sets of data, the program develops culvert performance data with or without overtopping. A performance curve can be plotted on a computer with graphics capabilities by typing a **P** for plot. This, and other graphics, may be printed using the print screen keys if the GRAPHICS.COM (CGA, EGA, VGA drivers) or MSHERC.COM (Hercules monochrome driver) was invoked prior to initiating the HY8 session.

A minimization routine allows the designer to enter an allowable headwater elevation which will be used to adjust the culvert size. The program will increase or decrease the culvert size until it computes a controlling headwater elevation lower than the defined allowable headwater for the design discharge. Several hydraulic parameters such as the controlling headwater elevation, inlet and outlet control elevation, culvert flow velocity, channel flow velocity, culvert flow depth, channel flow depth, and normal and critical depth will be recomputed when the minimization routine is activated. This routine is activated by selecting letter **M** from the options shown in the Options Menu screen. Only culvert number one can be minimized.

Summary screens allow the user to edit entered data or change menu selections. Output screens display the output as calculations proceed; hard copy is obtained using the "print screen" key or by selecting a print-out of the culvert analysis summary from the performance curve output screen. Output file may be directed to the screen, printer, or a file (having the standard HYDRAIN **.LST** extension).

FHWA CULVERT ANALYSIS
HY8, VERSION 6.1
SUMMARY TABLE

DATE: 10-15-97
TIME: 15:50:10

C U L V NO. 1	<S> SITE DATA			<C> CULVERT SHAPE, MATERIAL, INLET				
	INLET ELEV. (m)	OUTLET ELEV. (m)	CULVERT LENGTH (m)	BARRELS SHAPE MATERIAL	SPAN (m)	RISE (m)	MANNING n	INLET TYPE
	30.00	29.50	60.00	1 - RCB	652	652	.012	CONVENTIONAL

HEADWATER ELEVATIONS (m)			FLOW VELOCITY (m/s)			FLOW DEPTHS (m)		
ENTER ALLOWABLE	=	31.00	CULVERT	=	2.63	CULVERT	=	0.36
CONTROLLING	=	30.68	CHANNEL	=	1.05	CHANNEL	=	0.26
INLET CONTROL	=	30.68	DISCHARGE	=	0.50	NORMAL	=	0.39
OUTLET CONTROL	=	30.41	SLOPE	=	0.0083	CRITICAL	=	0.45

MAXIMUM HEADWATER <ENTER > TO RETURN <S> TO SAVE FILE
<H> TO CHANGE HEADWATER

Figure 4. Data summary table screen.

The output includes a performance table for individual culverts in the roadway so that culverts can be compared using plots. A performance table for multiple culverts is provided which contains for each total discharge and headwater the discharge in each barrel and discharge over the roadway. The user can display a table for each culvert that contains: tailwater elevation, inlet and outlet control headwater depths, USGS flow types, flow profile types, crest control, throat control and face control elevations, and outlet velocity. The user can also choose to view the inlet and outlet control curves (plots) and computational error table or print a report. The summary of the culvert analysis can be printed to the screen, printed to the printer or stored on diskette.

Help screens are operational throughout HY8 by pressing <F1>. Pressing <F2> displays a list of the various authors that have contributed to the HY8 program. HY8 can be exited by pressing <F5>. HY8 can be temporarily exited to DOS by striking <F9>. The CSU editor can be accessed by striking <F7>. These function keys are operational whenever they are displayed at the bottom of any HY8 screen.

A print-out of the summarized culvert analysis can be obtained by selecting the appropriate options depicted under the performance curve table for overtopping. Whenever possible, the SAVE option should be selected to ensure that data are placed on a file for later reuse or editing.

Other HY8 Program Modules

Given the basics of using the culvert analysis program module, other HY8 modules (Hydrology, Routing, and Energy Dissipation) are accessed in a similar manner. To leave the HY8 program, select the "RETURN TO DOS" option in the HY8 program menu. At this point, the user will be returned to either the HYDRAIN System Shell, or the DOS prompt, depending on the manner HY8 was initially accessed.

APPENDIX A. BENCHMARK EXAMPLES

The following examples are hypothetical systems modeled by HY8 which illustrate some of the program's capabilities. It should be recognized that these examples are not meant to give a comprehensive guide of every program. These examples demonstrates how culvert hydraulic analysis and design can be accomplished using HY8. At the HY8 options menu, the user selects the option, "<C> Create", to enter the culvert analysis and design module. Additional examples may be found in Ginsberg.[(6)] The intent is that these examples will achieve at least these two objectives:

1. Provide information on how to set up a problem.

2. Demonstrate what to expect for output.

The examples include a figure to schematically represent the problems. Each example provides the output data set developed by the run. Each of the examples provides a different type of HY8 application. The applications are:

1. Designing a box culvert curve.

2. Multiple culvert analyses.

Example One: Peak Flow Box Culvert Design

Problem: A box culvert located at the site shown in figure 5 is to be designed to pass a flow of 6.2 m^3/s without reaching within 0.3 m of the roadway elevation (i.e., 0.3 m of freeboard). Also the culvert crown must be at least 1 m below the road surface. The freeboard and cover requirements provide the design criteria of a 1.220-m maximum culvert rise and a 2.0-m allowable headwater, respectively. The inlet is a square headwall with 1 to 1.5 bevels (used to reduce entrance losses). The example uses an irregular channel shape to generate the tailwater rating curve. The Manning's n value in the channel is 0.03 and 0.1 in the overbank areas. The site data also provides roadway information so the example can consider roadway overtopping. A maximum flow of 14.2 m^3/s sets the upper bound of the performance curve. The interactive program prompts for the needed data. Call the input file HY81.

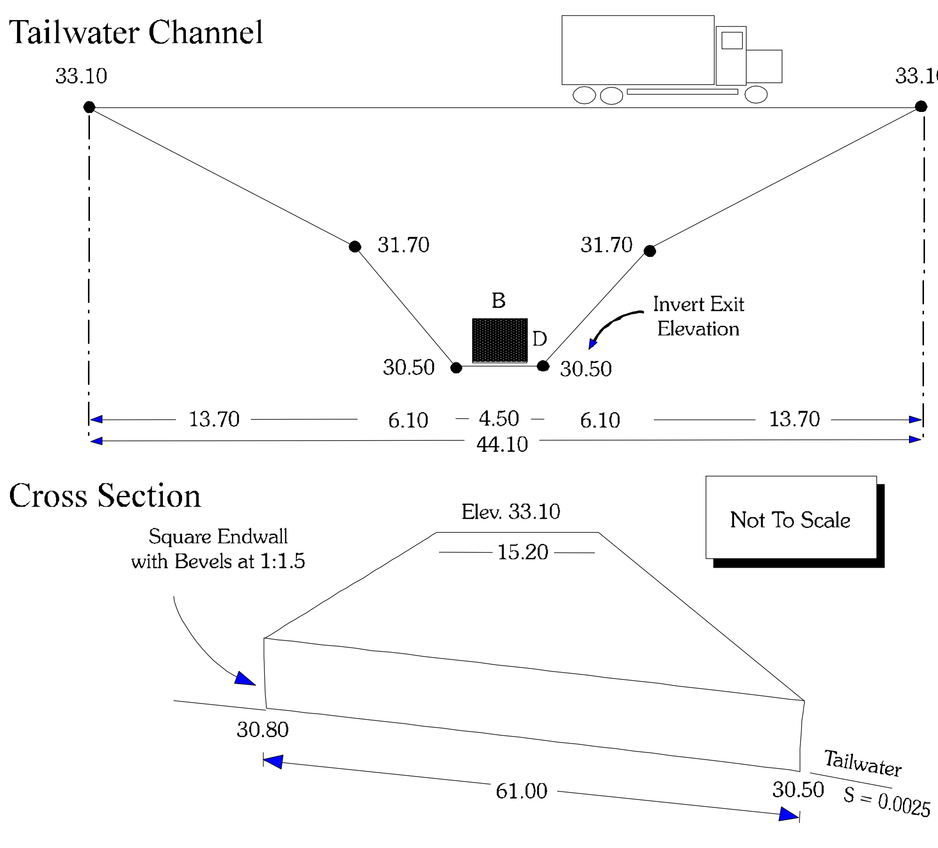

Figure 5. Site data for example one.

Input:

After creating a file called HY81, the user will be prompted for discharge range, site data, and culvert characteristics (shape, size, material and inlet type). The discharge range for this example will be from 0 to 14.2 m^3/s. The design flow will equal 6.2 m^3/s, based on the use of USGS regression equations at the site.

As an initial estimate, select a 1.220-m by 1.220-m concrete box culvert. As each group of culvert data is entered the user is allowed to edit any incorrect entries.

After all culvert data is entered, the program will prompt for data pertaining to the channel so that tailwater rating curve can be determined. After entering the irregular channel information, pressing <P> will cause the computer to display the channel cross section. The user can easily identify any input errors by glancing at the plot.

The program now has enough information to develop a uniform flow rating curve for the channel and provide the user with a list of options. Selecting option (T) on the Irregular Channel Data Menu will make the program compute the rating curve data. Selecting option (I) will permit the user to interpolate data between calculated points.

The Tailwater Rating Curve table consists of tailwater elevation at normal depth, natural channel velocity, and the shear stress at the bottom of the channel for various flow rates. Entering <P> will cause the computer to display the rating curve for the channel.

The next prompts are for the roadway profile, so that an overtopping analysis can be performed. Assume the roadway profile is a constant, level surface The other data required for overtopping analysis are roadway surface or weir coefficient and the embankment top width. For this example, the roadway is paved with an embankment width of 15.20 m. Once all data is entered, HY8 takes the user to the Data Summary screen.

Minimize Culvert Span

Use the Minimize Culvert Span option to see if the 1.220-m by 1.220-m box culvert can meet the allowable headwater constraints. Minimize is option M in the Data Summary screen. After selecting this option, HY8 prompts for the allowable headwater elevation. Once the value is entered (32.50 m), the program designs a culvert size that passes the allowable headwater at the design flow. The resulting culvert size is a 1.83-m by 1.220-m box culvert. Leave the Minimize option and press <Enter> to perform additional analysis on the culvert.

Output:

The culvert performance curve table can be obtained by selecting option (O). When option (O) is selected, the program will compute the performance curve table, considering overtopping in the analysis. Once the overtopping calculations have finished, the program will provide and opportunity to create output reports. The report for example one follows.

Output File: HY81.LST

CURRENT DATE: 05-01-1997 FILE DATE: 05/01/97
CURRENT TIME: 06:01:00 FILE NAME: HY81

))
))))))))))))))))))))))))))) FHWA CULVERT ANALYSIS))))))))))))))))))))))))))
))))))))))))))))))))))))))) HY-8, VERSION 6.1))))))))))))))))))))))))))

C	SITE DATA			CULVERT SHAPE, MATERIAL, INLET				
U L V NO.	INLET ELEV. (m)	OUTLET ELEV. (m)	CULVERT LENGTH (m)	BARRELS SHAPE MATERIAL	SPAN (mm)	RISE (mm)	MANNING n	INLET TYPE
1	30.80	30.50	61.00	1 - RCB	1830	1220	.012	CONVENTIONAL
2								
3								
4								
5								
6								

))
SUMMARY OF CULVERT FLOWS (m3/s) FILE: HY81 DATE: 05-01-1997

ELEV (m)	TOTAL	1	2	3	4	5	6	ROADWAY	ITR
30.80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1
31.40	1.4	1.4	0.0	0.0	0.0	0.0	0.0	0.00	1
31.76	2.8	2.8	0.0	0.0	0.0	0.0	0.0	0.00	1
32.06	4.3	4.3	0.0	0.0	0.0	0.0	0.0	0.00	1
32.36	5.7	5.7	0.0	0.0	0.0	0.0	0.0	0.00	1
32.47	6.2	6.2	0.0	0.0	0.0	0.0	0.0	0.00	1
33.10	8.5	8.5	0.0	0.0	0.0	0.0	0.0	0.00	1
33.16	9.9	8.7	0.0	0.0	0.0	0.0	0.0	1.15	5
33.20	11.4	8.8	0.0	0.0	0.0	0.0	0.0	2.46	4
33.24	12.8	8.9	0.0	0.0	0.0	0.0	0.0	3.71	3
33.27	14.2	9.0	0.0	0.0	0.0	0.0	0.0	5.05	3
33.10	8.5	8.5	0.0	0.0	0.0	0.0	0.0	OVERTOPPING	

))

))
SUMMARY OF ITERATIVE SOLUTION ERRORS FILE: HY81 DATE: 05-01-1997

HEAD ELEV (m)	HEAD ERROR (m)	TOTAL FLOW (m3/s)	FLOW ERROR (m3/s)	% FLOW ERROR
30.80	0.000	0.00	0.00	0.00
31.40	0.000	1.42	0.00	0.00
31.76	0.000	2.84	0.00	0.00
32.06	0.000	4.26	0.00	0.00
32.36	0.000	5.68	0.00	0.00
32.47	0.000	6.20	0.00	0.00
33.10	0.000	8.52	0.00	0.00
33.16	-0.002	9.94	0.07	0.70
33.20	-0.001	11.36	0.06	0.52
33.24	-0.002	12.78	0.12	0.98
33.27	-0.002	14.20	0.12	0.82

))
<1> TOLERANCE (m) = 0.003 <2> TOLERANCE (%) = 1.000

CURRENT DATE: 05-01-1997 FILE DATE: 05-01-1997
CURRENT TIME: 13:12:44 FILE NAME: HY81

PERFORMANCE CURVE FOR CULVERT 1 - 1(1830 mm BY 1220 mm) RCB

DIS- CHARGE FLOW (m3/s)	HEAD- WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	30.80	0.00	-0.30	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
1.42	31.40	0.60	0.55	1-S2n	0.34	0.40	0.30	0.34	2.55	0.69
2.84	31.76	0.96	0.78	1-S2n	0.54	0.63	0.55	0.49	2.84	0.84
4.26	32.06	1.26	1.07	1-S2n	0.73	0.82	0.70	0.60	3.33	0.94
5.68	32.35	1.55	1.42	5-S2n	0.90	1.00	0.87	0.70	3.55	1.02
6.20	32.47	1.67	1.57	5-S2n	0.96	1.05	0.93	0.73	3.63	1.05
8.52	33.10	2.25	2.30	6-FFc	1.22	1.22	1.22	0.85	3.82	1.14
8.72	33.16	2.30	2.36	6-FFc	1.22	1.22	1.22	0.92	3.91	1.19
8.85	33.20	2.34	2.40	6-FFc	1.22	1.22	1.22	0.98	3.96	1.23
8.94	33.24	2.37	2.44	6-FFc	1.22	1.22	1.22	1.03	4.01	1.27
9.03	33.27	2.40	2.47	6-FFc	1.22	1.22	1.22	1.09	4.05	1.30

El. inlet face invert 30.80 m El. outlet invert 30.50 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

***** SITE DATA ***** CULVERT INVERT **************

INLET STATION	0.00 m
INLET ELEVATION	30.80 m
OUTLET STATION	61.00 m
OUTLET ELEVATION	30.50 m
NUMBER OF BARRELS	1
SLOPE (V/H)	0.0049
CULVERT LENGTH ALONG SLOPE	61.00 m

***** CULVERT DATA SUMMARY ************************

BARREL SHAPE	BOX
BARREL SPAN	1830 mm
BARREL RISE	1220 mm
BARREL MATERIAL	CONCRETE
BARREL MANNING'S n	0.012
INLET TYPE	CONVENTIONAL
INLET EDGE AND WALL	1.5:1 BEVEL (90 DEG.)
INLET DEPRESSION	NONE

```
CURRENT DATE: 05-01-1997                                FILE DATE: 05-01-1997
CURRENT TIME: 13:12:44                                  FILE NAME: HY81

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))))))))))))))))))))))))))         TAILWATER        ))))))))))))))))))))))))))
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***** USER DEFINED CHANNEL CROSS-SECTION                 FILE NAME: HY81
      MAIN CHANNEL AND LT & RT OVER BANKS                FILE DATE: 01/01/96
      LEFT CHANNEL BOUNDARY           2
      RIGHT CHANNEL BOUNDARY          5
      MANNING n LEFT OVER BANK        0.100
      MANNING n MAIN CHANNEL          0.030
      MANNING n RIGHT OVER BANK        0.100
      SLOPE OF CHANNEL                0.0025 m/m

      CROSS-SECTION    X          Y
        COORD. NO.     (m)        (m)
            1           0.00      33.10
            2          13.70      31.70
            3          19.80      30.50
            4          24.30      30.50
            5          30.40      31.70
            6          44.10      33.10

******* UNIFORM FLOW RATING CURVE FOR DOWNSTREAM CHANNEL

        FLOW     W.S.E.  FROUDE   DEPTH    VEL.   SHEAR
        (m3/s)     (m)   NUMBER     (m)   (m/s)    (Pa)
         0.00     30.50   0.000    0.00    0.00    0.00
         1.42     30.84   0.424    0.34    0.69    6.46
         2.84     30.99   0.446    0.49    0.84    8.71
         4.26     31.10   0.459    0.60    0.94   10.39
         5.68     31.20   0.468    0.70    1.02   11.73
         6.20     31.23   0.471    0.73    1.05   12.16
         8.52     31.35   0.481    0.85    1.14   13.84
         9.94     31.42   0.486    0.92    1.19   14.70
        11.36     31.48   0.490    0.98    1.23   15.51
        12.78     31.53   0.494    1.03    1.27   16.28
        14.20     31.59   0.497    1.09    1.30   17.00
Note: Shear stress was calculated using R.

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      ROADWAY SURFACE                             PAVED
      EMBANKMENT TOP WIDTH                        15.24 m
      CREST LENGTH                                44.10 m
      OVERTOPPING CREST ELEVATION                 33.10 m

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Example Two: Multiple Culvert Analysis

Problem: This example demonstrates that HY8 can analyze up to six culvert systems, with different barrel shapes, roughness, inverts, and/or slopes during the same run. For this example, use HY8 to concurrently analyze a single barrel, 1.220-m by 1.220-m reinforced concrete box (RCB) and a single barrel, 1.220-m diameter, corrugated steel pipe (CSP). Assume that while the RCB is at the same invert elevation as example one, the CSP inverts are 0.150 m higher in elevation (i.e., upstream invert at 30.80 m, downstream invert at 30.50-m elevation). Otherwise, assume the culvert data is the same as example one. The design flow for this example is 11.3 m^3/s with flows up to 28.3 m^3/s being analyzed. Once again, the roadway profile is a constant level surface. The tailwater rating curve derived for example one can be used again in this example. Call the input file HY82 so the original file does not get overwritten.

Do not use the minimize option (it only works on one culvert system), but after entering all the data, proceed to the overtopping analysis option. Selecting the print option enables an output file HY82.LST to be written to the disk.

Output File: HY82.LST

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                                                                           1

CURRENT DATE: 05-01-1997                                 FILE DATE: 05/01/97
CURRENT TIME: 13:24:14                                   FILE NAME: HY82

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))))))))))))))))))))))))))    FHWA CULVERT ANALYSIS    ))))))))))))))))))))))))))
))))))))))))))))))))))))))     HY-8, VERSION 6.1       ))))))))))))))))))))))))))
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C	SITE DATA			CULVERT SHAPE, MATERIAL, INLET				
U L V NO.	INLET ELEV. (m)	OUTLET ELEV. (m)	CULVERT LENGTH (m)	BARRELS SHAPE MATERIAL	SPAN (mm)	RISE (mm)	MANNING n	INLET TYPE
1	30.80	30.50	61.00	1 - RCB	1220	1220	.012	CONVENTIONAL
2	30.95	30.65	61.00	1 - CSP	1220	1220	.024	CONVENTIONAL
3								
4								
5								
6								

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SUMMARY OF CULVERT FLOWS (m3/s)        FILE: HY82              DATE: 05-01-1997

 ELEV (m)    TOTAL       1       2       3       4       5       6  ROADWAY ITR
    30.80      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.00  0
    31.44      1.4     1.0     0.4     0.0     0.0     0.0     0.0     0.00  4
    31.78      2.8     1.8     1.0     0.0     0.0     0.0     0.0     0.00  3
    32.14      4.3     2.5     1.8     0.0     0.0     0.0     0.0     0.00  4
    32.53      5.7     3.3     2.4     0.0     0.0     0.0     0.0     0.00  6
    32.86      6.2     3.5     2.7     0.0     0.0     0.0     0.0     0.00  5
    33.18      8.5     3.8     3.0     0.0     0.0     0.0     0.0     1.66  5
    33.22      9.9     3.9     3.0     0.0     0.0     0.0     0.0     3.01  4
    33.25     11.4     3.9     3.0     0.0     0.0     0.0     0.0     4.40  4
    33.28     12.8     4.0     3.0     0.0     0.0     0.0     0.0     5.69  3
    33.31     14.2     4.2     3.1     0.0     0.0     0.0     0.0     6.93  3
    33.10      6.7     3.8     2.9     0.0     0.0     0.0     0.0 OVERTOPPING
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  SUMMARY OF ITERATIVE SOLUTION ERRORS   FILE: HY82            DATE: 05-01-1997

        HEAD           HEAD             TOTAL          FLOW           % FLOW
       ELEV (m)     ERROR (m)       FLOW (m3/s)    ERROR (m3/s)       ERROR
        30.80          0.000             0.00          0.00             0.00
        31.44         -0.002             1.42          0.01             0.58
        31.78          0.001             2.84         -0.00            -0.16
        32.14          0.002             4.26         -0.01            -0.17
        32.53          0.002             5.68         -0.01            -0.15
        32.86         -0.003             6.20          0.01             0.20
        33.18         -0.002             8.52          0.05             0.53
        33.22         -0.003             9.94          0.05             0.51
        33.25         -0.002            11.36          0.03             0.25
        33.28         -0.001            12.78          0.08             0.66
        33.31         -0.001            14.20          0.05             0.35
))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))
  <1> TOLERANCE (m)  = 0.003                        <2> TOLERANCE (%) = 1.000
))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))
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CURRENT DATE: 05-01-1997 FILE DATE: 05-01-1997
CURRENT TIME: 14:13:37 FILE NAME: HY82

PERFORMANCE CURVE FOR CULVERT 1 - 1(1220 mm BY 1220 mm) RCB

DIS- CHARGE FLOW (m3/s)	HEAD- WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	30.80	0.00	-0.30	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
1.03	31.44	0.64	0.63	1-S2n	0.38	0.42	0.39	0.34	2.18	0.69
1.85	31.78	0.95	0.98	1-S2n	0.58	0.62	0.58	0.49	2.61	0.84
2.50	32.14	1.16	1.34	5-S2n	0.73	0.76	0.73	0.60	2.80	0.94
3.27	32.67	1.39	1.87	5-S2n	0.90	0.90	0.90	0.70	2.98	1.02
3.50	32.83	1.47	2.03	2-M2c	0.95	0.94	0.94	0.73	3.04	1.05
3.85	33.17	1.57	2.37	2-M2c	1.02	1.01	1.01	0.85	3.13	1.14
3.88	33.22	1.58	2.42	2-M2c	1.03	1.01	1.01	0.92	3.14	1.19
3.92	33.25	1.60	2.45	2-M2c	1.04	1.02	1.02	0.98	3.15	1.23
3.96	33.28	1.61	2.48	3-M2t	1.05	1.03	1.04	1.03	3.14	1.27
4.16	33.48	1.68	2.68	3-M2t	1.09	1.06	1.09	1.09	3.13	1.30

El. inlet face invert 30.80 m El. outlet invert 30.50 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

***** SITE DATA ***** CULVERT INVERT **************

INLET STATION	0.00 m
INLET ELEVATION	30.80 m
OUTLET STATION	61.00 m
OUTLET ELEVATION	30.50 m
NUMBER OF BARRELS	1
SLOPE (V/H)	0.0049
CULVERT LENGTH ALONG SLOPE	61.00 m

***** CULVERT DATA SUMMARY ************************

BARREL SHAPE	BOX
BARREL SPAN	1220 mm
BARREL RISE	1220 mm
BARREL MATERIAL	CONCRETE
BARREL MANNING'S n	0.012
INLET TYPE	CONVENTIONAL
INLET EDGE AND WALL	1.5:1 BEVEL (90 DEG.)
INLET DEPRESSION	NONE

CURRENT DATE: 05-01-1997 FILE DATE: 05-01-1997
CURRENT TIME: 14:13:37 FILE NAME: HY82

PERFORMANCE CURVE FOR CULVERT 2 - 1(1220 mm BY 1220 mm) CSP

DIS-CHARGE FLOW (m3/s)	HEAD-WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	30.95	0.00	-0.30	0-NF	0.00	0.00	0.00	-0.15	0.00	0.00
0.38	31.44	0.41	0.49	2-M2c	0.41	0.32	0.32	0.19	1.54	0.69
0.99	31.78	0.75	0.83	2-M2c	0.71	0.53	0.53	0.34	2.02	0.84
1.77	32.13	1.05	1.18	2-M2c	1.22	0.73	0.73	0.45	2.44	0.94
2.42	32.52	1.28	1.57	2-M2c	1.22	0.85	0.85	0.55	2.77	1.02
2.68	32.86	1.38	1.91	2-M2c	1.22	0.90	0.90	0.58	2.92	1.05
2.97	33.18	1.49	2.23	2-M2c	1.22	0.94	0.94	0.70	3.07	1.14
2.99	33.20	1.50	2.25	2-M2c	1.22	0.94	0.94	0.77	3.08	1.19
3.01	33.25	1.51	2.30	2-M2c	1.22	0.95	0.95	0.83	3.09	1.23
3.04	33.28	1.52	2.33	2-M2c	1.22	0.95	0.95	0.88	3.11	1.27
3.06	33.31	1.53	2.36	2-M2c	1.22	0.96	0.96	0.94	3.12	1.30

El. inlet face invert 30.95 m El. outlet invert 30.65 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

***** SITE DATA ***** CULVERT INVERT **************

INLET STATION	0.00 m
INLET ELEVATION	30.95 m
OUTLET STATION	61.00 m
OUTLET ELEVATION	30.65 m
NUMBER OF BARRELS	1
SLOPE (V/H)	0.0049
CULVERT LENGTH ALONG SLOPE	61.00 m

***** CULVERT DATA SUMMARY ************************

BARREL SHAPE	CIRCULAR
BARREL DIAMETER	1220 mm
BARREL MATERIAL	CORRUGATED STEEL
BARREL MANNING'S n	0.024
INLET TYPE	CONVENTIONAL
INLET EDGE AND WALL	BEVELED EDGE (1.5:1)
INLET DEPRESSION	NONE

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CURRENT DATE: 05-01-1997                                        FILE DATE: 05-01-1997
CURRENT TIME: 14:13:37                                          FILE NAME: HY82

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***** USER DEFINED CHANNEL CROSS-SECTION                        FILE NAME: HY82
      MAIN CHANNEL AND LT & RT OVER BANKS                       FILE DATE: 01/01/96
      LEFT CHANNEL BOUNDARY           2
      RIGHT CHANNEL BOUNDARY          5
      MANNING n LEFT OVER BANK        0.100
      MANNING n MAIN CHANNEL          0.030
      MANNING n RIGHT OVER BANK        0.100
      SLOPE OF CHANNEL                0.0025 m/m

      CROSS-SECTION    X          Y
        COORD. NO.     (m)        (m)
            1           0.00      33.10
            2          13.70      31.70
            3          19.80      30.50
            4          24.30      30.50
            5          30.40      31.70
            6          44.10      33.10

******* UNIFORM FLOW RATING CURVE FOR DOWNSTREAM CHANNEL

        FLOW     W.S.E.  FROUDE   DEPTH    VEL.   SHEAR
        (m3/s)    (m)    NUMBER    (m)    (m/s)    (Pa)
         0.00     30.50   0.000    0.00    0.00    0.00
         1.42     30.84   0.424    0.34    0.69    6.46
         2.84     30.99   0.446    0.49    0.84    8.71
         4.26     31.10   0.459    0.60    0.94   10.39
         5.68     31.20   0.468    0.70    1.02   11.73
         6.20     31.23   0.471    0.73    1.05   12.16
         8.52     31.35   0.481    0.85    1.14   13.84
         9.94     31.42   0.486    0.92    1.19   14.70
        11.36     31.48   0.490    0.98    1.23   15.51
        12.78     31.53   0.494    1.03    1.27   16.28
        14.20     31.59   0.497    1.09    1.30   17.00
Note: Shear stress was calculated using R.

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      ROADWAY SURFACE                           PAVED
      EMBANKMENT TOP WIDTH                      15.24 m
      CREST LENGTH                              44.10 m
      OVERTOPPING CREST ELEVATION               33.10 m

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